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Modelling of 200 MHz Surface Acoustic Wave (Saw) Delay Line for Sensor Specific Applications

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Abstract

Currently, Surface Acoustic Wave(SAW) devices find themselves in many common commercial applications like consumer electronics and telecommunications, where their ability to generate, condition and process radiofrequency (RF) signals is employed to manufacture on a large scale, devices like delay lines, bandpass filters, resonators, convolvers, radar pulse compression. filters, sensors, etc. This paper reports on the comparison of three methods of modelling SAW's. The three models are Impulse Response Model (IRM), Crossed-field Equivalent Circuit Model (ECM) and Coupling of Modes Model (COM). The results were used to calculate the insertion loss and bandwidth of SAW delay line using 50 finger pairs operating at a centre frequency of 200MHz. The modelling study was carried out using MATLAB® as a simulation tool. The results show that the SAW designs based on three models are adequate for sensor applications.

Keywords: *Coupling of Modes Model; Equivalent Circuit Model; Impulse Response model; Interdigital Transducer; Surface Acoustic Wave.*

1. INTRODUCTION

The surface acoustic wave (SAW) devices such as delay line, resonator, filter, oscillator, convolver, and correlator are used in communication and signal processing application (Ruppel, and Fieldly, 2000; Morgan, 2007; Royer and Dieulesaint, 1999; Gardner *et. al.* 2002; Raj, et al. 2013).The major factor in the development of SAW was the invention of Interdigital transducer(IDT). The IDT's consisting of two comb-like structures of metal electrodes made up of aluminium (Al)/ Chromium (Cr)/Gold (Au) material which are photo deposited onto a precisely oriented piezoelectric substrate, act as both transmitters and receivers of acoustic waves in a SAW device (Haresh M. Pandya *et. al.* 2013; Banu priya, *et. al.* 2014). The IDT's converts an electrical energy into acoustic energy and vice versa (Royer and Dieulesaint, 1999; Gardner *et. al.* 2002). SAW delay line as sensor is used for the detection and identification of various types of target gases that has been realized by making use of very basic property of SAW device (Banupriya *et. al.* 2015; 2016) fig. 1.

SAW delay line shown in Figure 1 consisting of two simple IDT structures. One IDT acts as the input or the transmitting IDT, to create SAW which then propagates through the length of the piezoelectric substrate towards the output or the receiving IDT's. Variation of the SAW travel length between the IDT's can be manipulated to get delays of different magnitude typically in the range of 1-50 µsec.

To streamline the direction of flow of SAW and confine it to only one direction, absorbers are used at the end of the device to attenuate it. Usually this loss is intrinsic and is around 6 dB for even a perfectly matched SAW transducer.

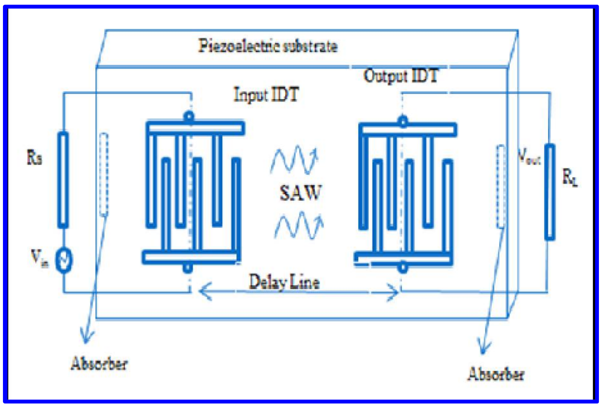

Fig. 1: SAW Delay Line

The delay produced by a SAW device can be expressed as

$$\tau = \frac{L}{v_0} \quad (1)$$

Where τ is the delay time, and L is the distance between the centres of the input and output IDT's.

2. THEORETICAL ANALYSIS

2.1 Impulse Response Model (IRM)

The impulse response model was first presented by Hartmann et al in 1973 as an improvement over the delta function model and is derived from the

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impulse response of a non-dispersive transducer (Hartmann, 1973). It is primarily a first order model that can be used as a fast tool to obtain information on the piezoelectric, mechanical and electrical behaviour of a SAW transducer as well as additional details regarding circuit impedances, matching networks and frequency scaling.

According to this model, the total energy is found from the impulse response and is equated to the radiation conductance, while the susceptance is derived from the conductance through the Hilbert transform. Moreover, the Fourier transform of the SAW device frequency response H(f) is the device impulse time response h(t).Hartmann was able to establish that the time response of a SAW IDT transducer (Pierce,1954) is given by,

$$h(t) \propto 4\sqrt{K^2C_s}f_0^{3/2}(t)\sin(2\pi f_0 t) \quad \text{for } 0 \le t \le \frac{N}{f_0} = 0 \qquad (2)$$

Where, K^2 is the electromechanical coupling coefficient, C_s is the electrode pair capacitance per unit length (pf/cm - pair) andf_0 the centre frequency of operation.

Taking Fast Fourier Transform (FFT)

$$H(f) = 20\log\left|\left[4K^2C_sWf_0N_p^2\left(\frac{\sin(X)}{X}\right)^2 e^{-j\left(\frac{N_p+D}{f_0}\right)}\right]\right| \qquad (3)$$

Where H(f) is frequency response of IDTs. W is aperture or finger overlap in the IDT, $N_p = M = N$ are the number of IDT finger pairs and D is the delay length in wavelengths between the IDT's. The variable defined as X in equation 3 is $N_p\pi\left(\frac{f-f_0}{f_0}\right)$ where, f is the instantaneous frequency at any instant of time t.
Insertion loss of the SAW delay line which is a function of frequency (Haus, 1977).

$$L(f) = -10\log\left[\frac{2G_a(f)R_g}{(1+G_a(f)R_g)^2+[R_g(2\pi fC_T+B_a(f))]^2}\right] \qquad (4)$$

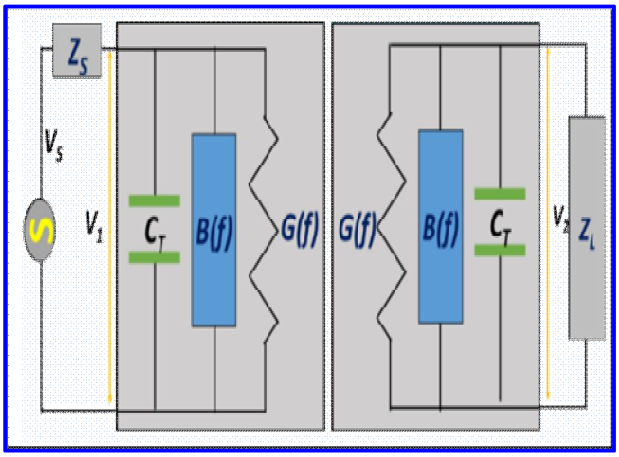

Fig. 2: Mason equivalent circuit for impulse response Model

2.1. Crossed-field Equivalent Circuit Model (ECM)

SAW propagation is modelled as electromagnetic (EM) signal propagation in a transmission line and includes signal generation due to an applied voltage, current generation in the load as well as losses and energy storage effects. Connection of mismatched transmission lines accounts for multiple reflections. The foremost advantage of this model offers is that it can be easily implemented in circuit simulation tools. The crossed-field model originated from the Mason equivalent circuit, which was employed for modelling Bulk Acoustic Wave devices (Sonics and Ultrasonics, 1977). In this model, the electric field distribution under the electrodes of an IDT is assumed to be normal to the piezoelectric surface, similar to the electric field distribution in a parallel plate capacitor (Fig. 3).

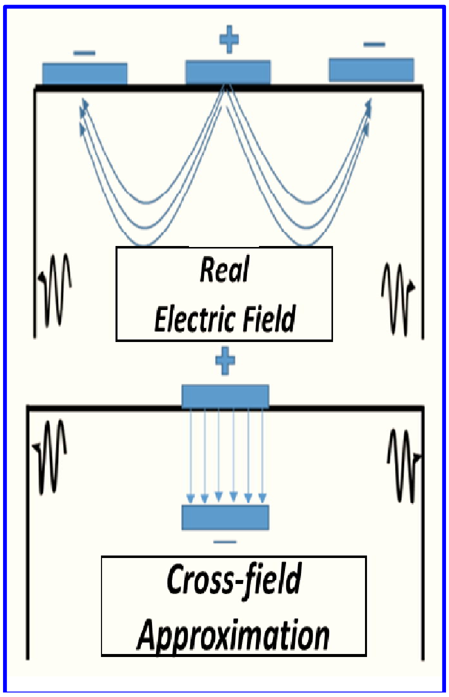

Fig. 3: Electric field Direction in Crossed-field ECM

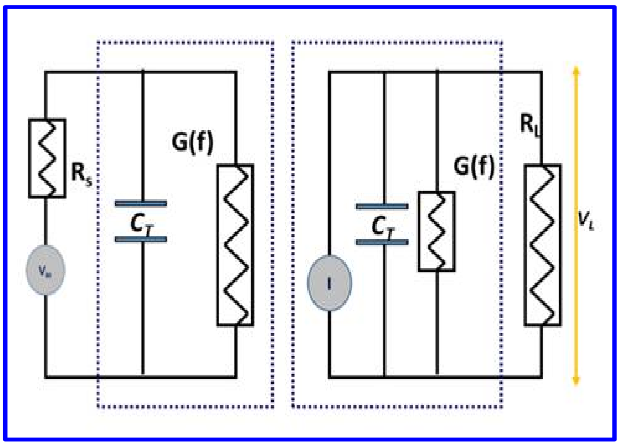

Fig. 4: Equivalent circuit for SAW delay line in crossed-field model

Utilizing circuit theory analysis for the current voltage relations on the input and output side of the equivalent circuit, the parameters like radiation conductance Ga(f), input admittance Y_{aa}, output admittance Y_{bb}, transfer admittance Y_{ab}, voltage transfer function and effective transmission loss are calculated. The corresponding equations are as follows,

- The input-output voltage transfer function $H(f)$ is,

$$H(f) = \frac{V_L}{V_{in}} = \left\{\frac{Y_{ab}R_L}{[(1+Y_{aa}R_S)+(1+Y_{bb}R_L)-Y_{ab}^2R_SR_L]}\right\} \quad (5)$$

The variations of transfer function $H(f)$ with frequency (f).

- Effective transmission loss (ETL) in decibels as defined by (Andle and Vetelino, 1994]

$$ETL = 20\log_{10}\left|\frac{[(1+Y_{aa}R_S)+(1+Y_{bb}R_L)-Y_{ab}^2R_SR_L]\sqrt{R_L/R_S}}{2R_LY_{ab}}\right| \quad (6)$$

2.3 Coupling-of- Modes (COM) Model

The Coupling-of-Modes (COM) theory is a refined method that was developed to describe the phenomenon of coupling of waves in microwave tubes in 1954 (Cavic *et. al.* 1999) and subsequently has been successfully applied in analyzing a wide range of devices including holograms (Kogelnik, 1969) and waveguide couplers in optoelectronics (Yariv, 1973). Haus (Haus, 1977; Haus, 1977) introduced the COM theory in SAW field. Since then COM theory has been widely used to analyse different types of SAW devices, such as resonators and single phase unidirectional transducers (SPUDTs). In all these devices, the reflection and transduction of acoustic waves is considered simultaneously.

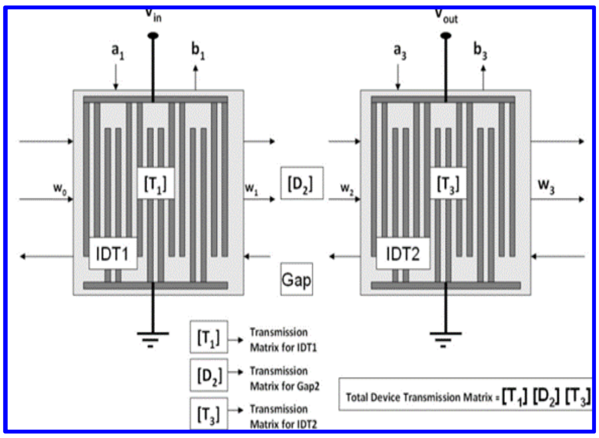

Fig. 5: COM matrix building blocks of SAW delay line

In the present study, the selected 200 MHz delay line was modelled as shown in figure 5. Where the delay line is represented in terms of its matrix building blocks (Haus and Huang, 1991), the mathematical theory being adopted based on (Haus and Huang1991). Here a delay line can be divided in to 3 segments, to represent input IDT, output IDT and the gap in-between them respectively. If these segments are represented by their transmission matrices, then the total device transmission matrix [M] is written as

$$[M]=[T_1]\ [D_2]\ [T_3] \quad (7)$$

The scattering matrix of an IDT is represented as (Haus and Huang, 1991; Joshi, and Sudhakar, 1977),

$$[T] = \begin{bmatrix} s(1+t_0)e^{j\theta_t} & -st_0 & t_{13} \\ st_0 & s(1-t_0)e^{-j\theta_t} & t_{13}e^{-j\theta_t} \\ st_{13} & -st_{13}e^{-j\theta_t} & t_{33} \end{bmatrix} \quad (8)$$

$[D_2]$ represents the 2x2 matrix of the gap in-between the IDT's and is given by

$$[D] = \begin{bmatrix} e^{j\beta d} & 0 \\ 0 & e^{-j\beta d} \end{bmatrix} \quad (9)$$

Where $\beta = 2\pi/\lambda$ is called the phase constant, d is the gap length and λ is the wavelength at the given frequency f.

3. MODELLING STRATEGY

In this paper, single and split electrode geometry SAW delay line of 200 MHz with 50 finger pairs in both IDT's with constant aperture is modelled using custom software developed in MATLAB®. The Impulse Response Model, Crossed field Equivalent Circuit Model and Coupling of Modes Model were selected and its underlying physics principles were employed to code programs (Sharma et al. 2014; Venkatesan, *et. al.* 2013; 2015).The input parameters of this SAW delay line are outlined in the table 1 and flowchart is shown in figure 6.

Table 1:The input parameters for Modelling of SAW Device

S.No	Parameter (Symbol)	Values
1	Coupling co-efficient(K^2)	0.0016 (Quartz)
2	SAW velocity (V)	3158m/s
3	Centre frequency (f_0)	200 MHz
4	IDT geometry	Single/Split geometry
5	Finger width	3.9475µm-SingleGeomentry 1.975µm-Split Geometry
6	Number of finger pairs (N)	50
7	Load resistance (R_L)	50 Ω
8	Source resistance (R_S)	50 Ω

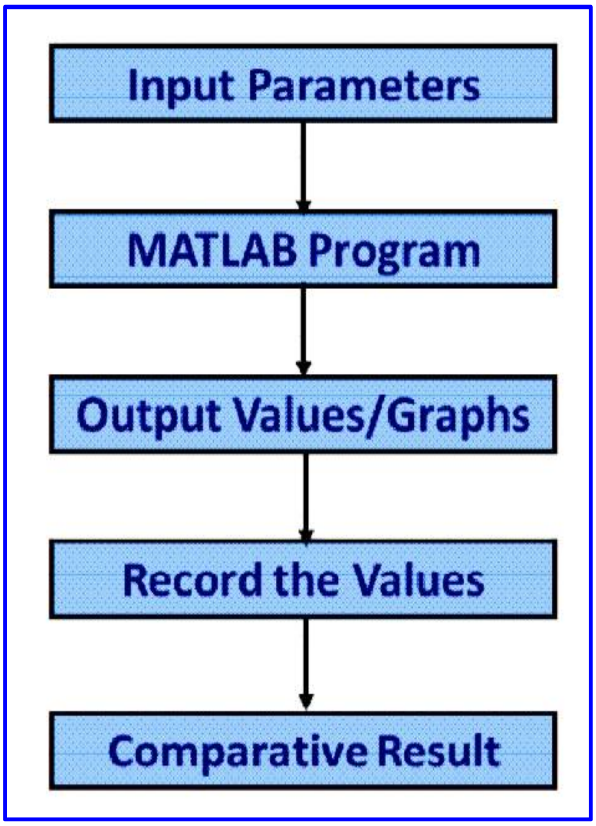

Fig. 6: Flow chart

4. RESULTS & DISCUSSION

MATLAB® program code was developed based on the SAW delay line device. The simulations were performed using a combination of software programming using Visual Basic of Microsoft Visual Studio as a front end tool and MATLAB®, as the main back end tool. Graphic results were imported to Microsoft Excel for viewing, analysis and comparison. The output results and their values are listed in table2.

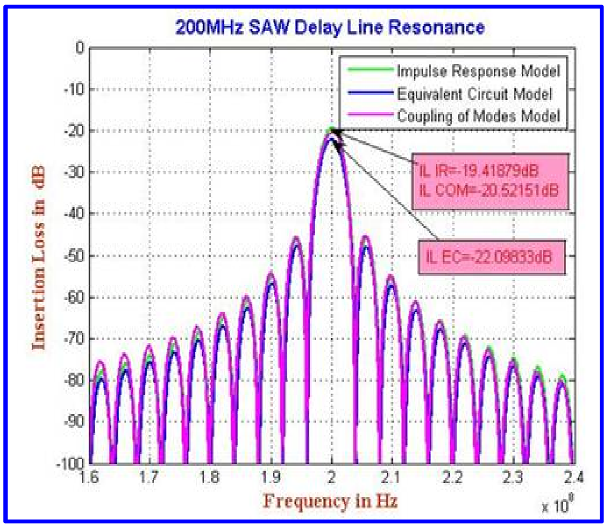

Fig. 7: Modelled Output Frequency Response for 200 MHz SAW Device with 50 Single IDT Geometry

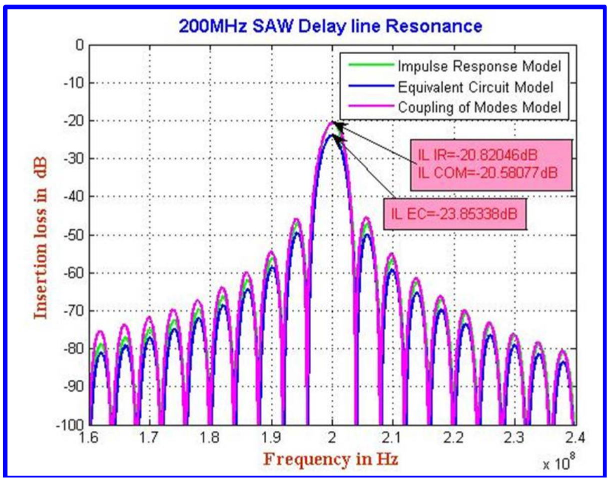

Fig. 7: Modelled output frequency response for 200 MHz SAW devicewith 50 Double IDT geometry

Table 2: Modelled output values of 200MHz SAW Delay Line

Model	Single IDT Geometry		Double IDT Geometry	
	Insertion Loss (dB)	Band width (in MHz)	Insertion Loss (dB)	Band width (dB)
IRM	-19.41879	2.5	-20.82046	2.5
ECM	-22.09833	2.6	-23.85338	2.6
COM	-20.52151	2.7	-20.58077	2.7

5. CONCLUSION

SurfaceAcoustic Wave Delay Line has been modelled as per three standard models-namely the Impulse Response Model, Equivalent Circuit Model and Coupling of Modes Model with 50 finger pairs operating at 200MHz. SAW device design parameters were optimized and its frequency response were obtained by employing a custom made MATLAB® algorithm. The result shows that the SAW device based on the three models are adequate for sensor applications.This simulation can be extended to other devices like SAW filter and SAW Sensors will form the crux of future studies related to the present research work.

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